



Fermi National Accelerator Laboratory

FERMILAB-Pub-85/138-T
September 1985

A NEW LEVEL OF STRUCTURE

O.W. Greenberg*

Department of Theoretical Physics
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

In the standard model of matter, there are five stages of compositeness --- molecules, atoms, nuclei, nucleons, and quarks and leptons --- but we are beginning to see regularities at the fifth layer that may point to a deeper, sixth level of structure.

To appear in Physics Today, September 1985

* Supported in part by the National Science Foundation. Visiting Scholar, Enrico Fermi Institute, University of Chicago. On sabbatical leave from the University of Maryland, August 1, 1984 - July 31, 1985.



The history of the physics of the small is in great measure the story of the discovery of new levels of structure, each associated with the development of a new set of experimental tools, and ultimately with a new discipline. We have repeatedly categorized some set of particles as the elementary constituents of matter, only to discover later that these should properly be considered as composed of yet-more-fundamental particles. Discounting the prescientific view of matter as composed of Air, Fire, Earth, and Water, five levels of structure have been discovered so far, as shown in box 1. Most readers of this article are probably familiar with the evidence for each level of structure. A good description of this evidence can be found in reference 1.

Economy

I would not require that a composite model have fewer basic particles than the standard model. There are cases in the past in which progress was associated with a temporary loss of economy. The step from the prescientific view of matter with four constituents to the atomic picture with some one hundred elements seemingly suffers from loss of economy, and just as clearly represents progress in our understanding of matter. The step from atoms labeled by the atomic number, Z , to nuclei labeled by both Z and the mass number A , also loses economy and also represents progress. We would like the "ultimate" theory to be economical, but if we renounce the utopian desire for an ultimate theory, then there is no reason to insist on numerical economy for each step to a deeper level. In addition, the true economy of a theory at a deeper level of structure is only revealed when the excited states are discovered.

Another important quest in physics is the attempt to unify types of forces and varieties of matter, which, at that stage of our understanding seem to be independent. The outstanding example of this unification is James Clerk

Maxwell's theory of electromagnetism, which unifies electric and magnetic forces, predicts the existence of electromagnetic radiation, and, together with quantum mechanics and the atomic picture of matter, leads to a unified understanding of intermolecular, molecular and atomic forces. Attempts at unification have, however, often failed: Witness the attempts made in the context of classical physics by Gustav Mie, Albert Einstein, Hermann Weyl, Theodor Kaluza, and Oskar Klein. In the context of quantum physics, P.A.M. Dirac made an early attempt at unification when he proposed to interpret the negative energy solutions of the Dirac equation --- which we now identify as positrons --- as protons, to provide a unified theory of the then-known elementary particles: the proton, electron and photon. In more recent times, attempts were made to make a "global symmetry" theory of the eight positive-parity baryons, and to use relativistic $SU(6)$ and higher symmetry groups as possible unification groups for hadrons. We now recognize that an economical description of hadrons comes about from understanding them as composed of quarks, rather than from imposing unification at the hadron level. The grand unified theories of quarks and leptons may similarly fall into the category of failed attempts. For example, in the grand unified theories there is an extremely large range of energies between the region where we now have experimental information and the energies at which one observes the unification directly; nothing interesting should happen in that range. It is, however, hard to believe that nothing should happen between 10^2 GeV and 10^{14} GeV. Further, the failure to detect proton decay --- the most striking prediction of the grand unified theories --- at the expected rate undermines our confidence in these theories.

While the standard model accounts for a vast range of data, it still leaves a great many parameters free to be fitted experimentally: the masses of

the fundamental quarks and leptons, the Cabibbo and other quark mixing angles, the weak mixing angle, as well as other parameters. The classical way to account for free parameters at a given level of structure is to go to a deeper level of structure. The history of the successes of composite models in predicting energy levels or masses in atomic, nuclear, and hadronic physics provides a powerful motivation to investigate the possibility that there is a new level of structure underlying quarks, leptons and some of the other particles of the standard model.

The purpose of this article is to consider the possibility of such a sixth level of compositeness. Following Jogesh C. Pati of the University of Maryland and Abdus Salam of the International Centre for Theoretical Physics at Trieste and the Imperial College in London, I call the constituents of the sixth level "preons." I suggest "diron" as a name for the elementary particles of matter, the fundamental quarks and leptons, of the standard model. All quarks and leptons are Fermi-Dirac particles, for which "fermion" is used as a generic name. I think it appropriate to associate Dirac's name with the fundamental particles at the level of the electron.

I have mentioned superstring theories (see Physics Today, July, page 17), supergravity and the Kaluza-Klein theories as other possible models for the properties of the dirons. However, these take us even further than the grand unified theories from the energy range that has been explored experimentally. I don't think these approaches are likely to resolve the present problems in elementary-particle physics.

I want to emphasize, however, that I believe that the insight into the structure of quantum field theory gained from research on grand unified theories, Kaluza-Klein theories, supergravity and superstring theories is likely to have important application, although perhaps in different contexts

from their present arenas of study --- just as Yang-Mills theories have become relevant to physical situations quite different from the nucleon isotopic-spin problem to which they were first applied.

The standard model

Before giving further motivations for composite models, I briefly describe the standard model, which is the most comprehensive description of elementary particles that has been confirmed experimentally. (For more information about the standard model, see "Unified theory of elementary-particle forces," by Howard Georgi and Sheldon L. Glashow in *Physics Today*, September 1980, page 30). The fermions of the standard model, which are the particles which constitute matter, are dirons --- quarks and leptons --- all having intrinsic spin $1/2$. Everyday matter is made of the "up" and "down" quarks, u and d , the electron e and the electron neutrino ν_e . Four other quarks and two other sets of leptons have been discovered. The six "flavors" of quarks and the six kinds of leptons are generally grouped into three "generations":

Generation	1	2	3
Quark doublets	$[u \ d]$	$[c \ s]$	$[t \ b]$
Lepton doublets	$[\nu_e \ e]$	$[\nu_\mu \ \mu]$	$[\nu_\tau \ \tau]$

The charged W bosons which mediate the weak interactions couple to certain linear combinations or "mixtures" of the six flavors of quarks (which have definite mass, that is, they are mass eigenstates). These mixtures are called weak-interaction eigenstates, and they can be thought of as a sort of "rotation" among the various flavors of quarks. For example, there are weakly interacting eigenstates of the form

$$d' = d \cos \theta_c + s \sin \theta_c$$

$$s' = -d \sin \theta_c + s \cos \theta_c .$$

The angle θ_c is called the Cabibbo angle. The numbers of particles in each of the three generations (with dirons counted as +1, and antidirons as -1) may be conserved. (I emphasize that generation-number conservation can apply to the weak-interaction eigenstates, but not to the mass-eigenstates). At present we do not know if there are more generations lying at higher masses. The repetition of generations is a major puzzle of elementary-particle physics, which I hope will be understood in terms of compositeness of dirons.

The quarks --- which come in three "colors" --- carry charges coupled to the strong interaction. The gauge theory of the color force is called quantum chromodynamics; it is associated with the symmetry group $SU(3)_c$, where c stands for color. Both the quarks and leptons carry weak charges and electromagnetic charge. The gauge theory of the weak and electromagnetic forces is associated with the product group $SU(2)_L \times U(1)_Y$, where L stands for left-handed and Y for weak hypercharge. The forces coupled to these charges are mediated by vector "gauge" particles: the eight color gluons for the color force, the W^\pm and Z^0 bosons for weak interactions, and the photon for electromagnetism. These gauge particles are called weylons, after Hermann Weyl, who introduced the gauge principle. The "electroweak" sector of the theory requires a doublet of "Higgs" scalars, which play an essential role in providing masses for the W 's and the Z , as well as for the quarks and leptons. (The Higgs scalars also break the initial electroweak symmetry down to the $U(1)$ symmetry of electromagnetism.) The Higgs scalars are the only particles of the standard model that have not yet been discovered.

Experimental constraints

Because the standard model accounts for the properties of leptons to high

accuracy, current experimental data impose constraints on the possible composite structure of its "elementary" particles. I will concentrate on constraints from three kinds of measurements:

- magnetic moments, or more specifically, $g-2$, where g is the gyromagnetic ratio,
- contact interactions
- rare processes.

I recommend reference 2 for a comprehensive survey of experimental constraints on compositeness and references 3 and 4 for surveys of theoretical ideas on compositeness and for further references.

If dirons, that is, quarks and leptons, are composed of preons, there is an energy, which I shall denote by Λ , around which dirons are dissociated into preons; that is, Λ/c^2 is the mass scale of compositeness. The radius of a composite diron is of order $\hbar c/\Lambda$. If the currently-known dirons are the ground states of a composite system, we can expect many excited partners of the dirons at energies of the order of Λ . (I argue below that Λ is greater than about 1 TeV.)

Magnetic moments. Stanley J. Brodsky and Sidney D. Drell of SLAC and, independently, Gordon L. Shaw and Dennis J. Silverman of the University of California at Irvine and Richard Slansky of Los Alamos showed that the agreement of experimental results for $g-2$ for the muon with the predictions of quantum electrodynamics imposes severe lower limits on the compositeness scale Λ for theories without chiral symmetry: above 3×10^3 TeV. With chiral symmetry, the constraint is much weaker; Λ must be above 600 GeV.

Contact interactions. Estia Eichten of Fermilab, Kenneth Lane of Ohio State and Michael Peskin of SLAC showed that composite particles that share common constituents generate "contact" interactions at low energy. In techni-

cal terms, such interactions have a Lagrangian density of the form

$$\mathcal{L}_{\text{eff}} = \sum_{A,B} (g_{AB}^2 / \Lambda^2) (\bar{\psi}_A \gamma^\mu \psi_A) (\bar{\psi}_B \gamma_\mu \psi_B) .$$

Here the sum is taken over left-handed and right-handed particles, that is A and B take on values "left" and "right" for particles with their spin and momentum pointing in the opposite or in the same direction, respectively. The field ψ is a four-component Dirac spinor field and the γ^μ are the (relativistic) 4×4 Dirac matrices; a sum over the repeated four-vector index μ is implied. The field ψ could refer to any of the fermions, for example, the electron. Figure 1 is a graph for such an interaction. Such graphs must occur for scattering of identical particles and antiparticles, because these must have constituents in common. These graphs give contributions that can look like Z^0 exchange. If the Z^0 is elementary, the fact that experimental results agree with the standard model gives a strong bound on the absence of such processes and thus on the scale of compositeness: Λ must be above 1 TeV. If the Z^0 is composite, then these graphs include the Z^0 exchange (but do not exactly equal that exchange) and the bound is less severe.

Rare processes. Certain processes that are allowed by energy-momentum conservation and electric-charge conservation have not been observed. The absence of such rare processes imposes constraints upon compositeness theories. Similarly, the smallness of certain matrix elements, such as that for $K^0 \rightarrow \bar{K}^0$, gives a bound on the scale of compositeness. Itzhak Bars of Yale University, now at the University of Southern California, has emphasized the importance of constraints due to rare processes. These constraints, in contrast to the first two types, are model dependent. For example, the muon has never been observed to decay into an electron and photon. The upper bound is less than once in every 10^{10} decays. If this decay is allowed, Λ must be

above 100 TeV, but if the decay is forbidden by a selection rule, such as conservation of generation number, for interactions among the preons, we can infer no bound at all. Similarly, the fact that $K_L \rightarrow \mu e$ less than once in 10^9 decays implies that Λ is above 100 TeV if the decay is not forbidden because of a symmetry or selection rule. In the standard model, K_L is a bound state of quarks, $d\bar{s}$, so this decay conserves generation, color and flavor, and thus appears to violate no conservation rules. The bound it places on compositeness thus seems particularly strong. However, the decay requires that generation follow the d to e transition and color follow the d to \bar{s} transition, so it is forbidden if the same preon carries both color and generation. These issues, as well as the more subtle $K^0-\bar{K}^0$ matrix element have been discussed recently in reference 5, where a composite scenario that closely mimics the standard model was given.

The problem of the diron masses. The three types of experimental constraints I have described provide numerical limits on the scale of compositeness. A different kind of constraint is given by the masses of the quarks and leptons themselves. Compare (see table 1) the mass and the bound on the size of the electron with the masses and sizes of the hydrogen atom and proton. It is striking that for all composite systems studied prior to quarks and leptons, the dimensionless quantity Mcr/\hbar , where M is the mass of the composite system and r is its size, is greater than one. For the electron, however, this quantity must be less than 10^{-6} . Effectively, electrons --- and quarks and leptons in general --- are massless compared to the scale that characterizes their binding. It seems likely that the near vanishing of this parameter is due to a symmetry rather than to a finely tuned cancellation. The chiral symmetry, which moderates the constraints due to $g-2$, also "protects" dirons from acquiring a mass of the order of the large compositeness scale. I will

have more to say about the issue of protecting fermion masses later in this article.

Which particles are composite?

With this concise description of the standard model and the experimental constraints on compositeness in mind, we consider which of the particles of the model should be taken as composite at the next level of structure.

The first candidates are the Higgs scalars. The "Higgs sector" is the least-attractive aspect of the standard model. The Higgs potential of the Lagrangian depends on arbitrary parameters, and the Higgs mass is not fixed by currently measured quantities. Although there are theoretical arguments that bound its mass in both directions, there is still a large allowed range, and despite extensive experimental searches, it remains, as I already mentioned, the sole undiscovered particle of the standard model. To make matters worse, the Higgs interactions are very sensitive to quantum corrections, and properties of the standard model that has been adjusted to work well in lowest order can be badly upset by quantum corrections to the Higgs sector. Technicolor theories replace the Higgs sector, with its arbitrary parameters and its spontaneous symmetry breaking, with a new set of "technifermions" interacting via a new "technicolor" strong gauge interaction that generates dynamical symmetry breaking. Technicolor binds technifermions into technicolor-singlet "technihadrons." The techni analogs of pions play the role of composite Higgs scalars that are "swallowed" by the W 's and the Z to give them mass. (Other technihadrons should appear as physical particles.) Thus technicolor models are a type of composite model.

The next candidates for compositeness are the dirons. The relatively large number (six) of flavors of quarks and leptons and their easy arrangement into generations is a superficial hint that they may be composite.

A stronger suggestion for compositeness comes from the fact, already mentioned, that diiron masses are completely undetermined in the standard model, and the fact that despite the considerable ingenuity of many partisans of grand unified theories, no convincing calculation of quark and lepton masses has been made. Just what is meant by the mass of a quark is subtle: the confinement of quarks to the interior of hadrons does not allow measurement of the mass of a quark in isolation. Because of the strong color force, the mass of a quark depends on the distance (or energy) scale at which it is measured. Roughly speaking, the short-distance (or current-algebra) mass is the mass that appears in the fundamental Lagrangian of quantum chromodynamics, and the long-distance (or constituent) mass is the relevant mass for estimating the mass of hadrons in terms of the masses of the quarks they contain.

In the standard model, the quark and lepton masses are proportional to the quark and lepton Higgs couplings. This origin of mass is likely to carry over to preon models. Then quark and lepton masses would be associated with the composite vertex functions connecting the Higgs particles and the quarks or leptons.

Previous experience has been that mass spectra are calculable in terms of a deeper level of structure: the Bohr model of the atom, the shell model of nuclei and the quark model of hadrons have all been highly successful in this regard. These examples lend strong support to the hope that a preon model of quarks and leptons will determine the mass spectrum of quarks and leptons.

The spectrum of the Lagrangian masses of the dirons (box 3) has some unusual properties. The spacing between dirons with the same quantum numbers increases rapidly with energy. By contrast, the spacings between atomic energy levels go to zero as the energy increases to the ionization energy, and the spacings between what are called Regge recurrences of the baryons are, to

good approximation, constant. Also, the spacing between the up and down dirons (that is, those on the same rows as u and d) in a given generation is larger than the spacing between generations.

In the standard model there appear several parameters that play the role of rotation angles in the space of the internal symmetries; they appear in the calculations of matrix elements and mass differences. Among these are the Cabibbo angle, --- which relates the strangeness-conserving and strangeness-nonconserving weak interactions of hadrons --- other angles associated with the difference between the mass eigenstates and the weak-interaction eigenstates for quarks (these occur in the "Kobayashi-Maskawa" mixing matrix), and the weak mixing angle which gives the mixing of the neutral gauge field associated with $SU(2)_L$ with the gauge field of $U(1)_Y$. These angles are all left arbitrary by the standard model. I hope that a preon model can also determine these parameters.

Next I come to the question of compositeness of the gauge bosons of the standard model. Unbroken local gauge theories, such as quantum chromodynamics and electromagnetism, have a beauty which suggests that they have a fundamental role in the description of nature. This beauty is marred in broken gauge theories such as the weak interactions; one can question their fundamental nature, and can take their gauge bosons, the W's and the Z, to be composite. A more concrete hint that weak interactions are not fundamental is given by our experience that all the short-range forces we have discovered up to now have turned out to be residual effects of long-range forces associated with an unbroken gauge theory operating at a deeper level of structure (see box 4). In particular, the analogy of the short-range strong interactions between hadrons as residual effects of the long-range color interactions of unbroken $SU(3)_C$ acting at the quark level, with the short-range weak interactions as

residual effects of the long-range forces between preons, is compelling. The long-range forces, which are called "metacolor" or "hypercolor" interactions, are associated with an $SU(N)_{mc}$ gauge theory acting at the preon level. In this analogy, the W's and Z are composite, with their preons bound by metacolor, just as the pions, rho's, omega's and other phenomenological mediators of the strong interactions have turned out to be composites of quarks bound by color forces.

In fact that there are simple models in which the Higgs bosons, the quarks and leptons, and the W's and the Z all share common constituents. It is thus even more appealing to consider all of these particles of the standard model as composite.

I would draw the line there. The remaining particles of the standard model, the photon and the color gluons, belong to unbroken local gauge theories, which are both beautiful theoretical constructs and have good experimental support. I would keep the photon and color gluons elementary. Nonetheless, some bold speculators have considered possible compositeness of photons and gluons, and even of the graviton. I will not discuss these speculations in this article.

Quantum Numbers

The first step in constructing composite models is the step of assigning quantum numbers to the preons to reproduce the quantum numbers of the dirons (quarks and leptons) and other particles of the standard model. There are three choices for types of constituents:

- bosons and fermions
- fermions only
- bosons and monopoles.

Bosons and fermions. In such a theory, one can assign flavor, color (and

possibly generation) to different constituents. In particular, one can assign flavor to a fermion, because that part of the weak interaction which sees flavor has a handed or "chiral" structure; and one can assign color to a boson, because the color interaction has a nonchiral or "vector" structure. Models of this kind have the virtue that no type of degree of freedom is repeated, so it is easy to avoid generating unwanted exotic states. In addition, such models allow the 't Hooft anomaly-matching conditions (which I will mention below) to be satisfied easily. Variants in which, for example, both the fermion and the boson carry color, lead to "exotic" particles, such as colored W's and leptons. Such models have a distinctive phenomenology and stand ready to be used if experiment requires them. In either case, this type of model departs from the pattern of quantum chromodynamics in which all the constituents (quarks, in that case) are fermions. Models with bosons and fermions as constituents can be specially constructed so that they have a symmetry-called "supersymmetry" --- that transforms bosons into fermions and vice versa. Such models, which I discuss below, are particularly interesting. (If supersymmetry is realized in nature, I would include "squarks" and "sleptons" --- the supersymmetric partners of quarks and leptons, and also constituents of matter --- among the dirons as well.)

As an example, consider the simplest boson-fermion model that provides the desired quantum numbers. The fermions F_{fA} are massless spin-1/2 preons carrying flavor ($f = u, d$) and handedness ($A = \text{left, right}$) quantum numbers. The bosons ϕ^α carry color for $\alpha = 1, 2, 3$ and lepton number for $\alpha = 4$. The fermions and, separately, the bosons are the N particles corresponding to a representation of the metacolor symmetry group $SU(N)_{mc}$, so that $F\phi^\dagger$ is a metacolor singlet. The electric charges, in units of $|e|$, are $+1/2$ and $-1/2$ for F_u and F_d , and $-1/6$ for $\phi^{1,2,3}$ and $+1/2$ for ϕ^4 .

Here is the first generation of quarks and leptons:

	Left-handed	Right-handed
Quark doublets	$u_L = F_{uL} \phi_\alpha^\dagger$ $d_L = F_{dL} \phi_\alpha^\dagger$	$u_R = F_{uR} \phi_\alpha^\dagger$ $d_R = F_{dR} \phi_\alpha^\dagger, \alpha = 1, 2, 3$
Lepton doublets	$\nu_{eL} = F_{uL} \phi_4^\dagger$ $e_L = F_{dL} \phi_4^\dagger$	$\nu_{eR} = F_{uR} \phi_4^\dagger$ $e_R = F_{dR} \phi_4^\dagger$

To include higher generations, one can add a generation index to the ϕ 's .

This model gives a right-handed neutrino, which is not present in the standard model, in addition to the usual 15 helicity states that make up a generation in the standard model. Thus the neutrinos in this model have mass.

I mentioned earlier that chiral symmetry is necessary to allow the compositeness scale Λ to be as low as about 1 TeV. In quantum chromodynamics, chiral symmetry is spontaneously broken, and the composite fermions, which are the baryons, acquire a mass that is actually greater than the quantum chromodynamic binding scale Λ_{QCD} . The particles that remain (approximately) massless are bosons: the pions and their SU(3) flavor partners. This scenario must not occur for preon models of quarks and leptons. At the least, we must identify differences between preon models and quantum chromodynamics that can allow chiral symmetry to be preserved in the former, even though it is broken in the latter.

Supersymmetric preon models differ from quantum chromodynamics in several ways. They have different matter constituents than quantum chromodynamics: bosons and fermions, rather than just fermions. Further, introducing super-

symmetric metacolor in place of the usual color forces provides both vector gluons and their supersymmetric partners, spin-1/2 gluinos, as mediators of the metacolor binding forces in place of the vector gluons of quantum chromodynamics. A product metacolor group in place of $SU(3)_c$ of quantum chromodynamics may also play a role in preserving chiral symmetry. One can speculate that because of these differences, chiral symmetry remains unbroken in supersymmetric preon models in contrast to the outcome in quantum chromodynamics. Later I will discuss a further mechanism to protect fermion masses from acquiring magnitudes of the order of the binding scale, the supersymmetric Nambu-Goldstone mechanism, which is available only in supersymmetric models.

Supersymmetry plays another role in boson-fermion models. Supersymmetry cures the problems that models with fundamental bosons suffer due to their quadratically divergent quantum corrections. With supersymmetry, the scalars are in the same supermultiplet as spinors and have their quantum corrections tamed by this association.⁶

Fermions only. When all the constituents are fermions, each of the quantum numbers --- flavor, color and generation --- can live on a different constituent. This assignment avoids producing exotic particles, that is, particles with quantum numbers that do not occur in the standard model. On the other hand, the same quantum numbers can be carried by more than one constituent; in that case the model generates exotics, but models have been constructed in which the exotics are kept out of harm's way. Just as in the boson-fermion case, one can call upon the models with exotics if experiment calls for them. An interesting type of assignment is to place the fermions in the fundamental spinor representation of $O(2N)$ groups. This has the possible virtue that such models connect well with the $O(2N)$ grand unified theories.

The rishon model --- introduced independently by Haim Harari of the

Weizmann Institute of Science and by Michael A. Shupe of the University of Illinois --- also has only fermionic constituents. The eight charge states that occur in each generation of quarks and leptons in the standard model can be constructed by using only two types of fermions: T whose charge is $1/3$, and V, whose charge is 0. The dirons are the eight arrangements of three-particle states, TTT; TTV, TVT, VTT; VVT, VTV, TVV; and VVV. In the original version of the rishon model, the authors suggested that the triplets of equally charged states, such as TTV, TVT, and VTT, could correspond to the three colors of quarks. Thus, the rishon model made a bold attempt to explain color on the basis of a composite model. Unfortunately, this attempt failed because these three states are linearly dependent in the original version of the model; furthermore, without other degrees of freedom there is no way to make only the desired states have an appropriately low energy. The attempt to repair this difficulty led to a more complicated model which, unfortunately, suffered from other theoretical problems, as well as being less bold.

Bosons only. Models with only bosonic constituents avoid the necessity of having fermions by using the bound states of monopoles to provide both spin and Fermi-Dirac statistics for the fermions. So far, aside from some pioneering work by Pati, such models have received little attention.

I will concentrate on the boson-fermion model in this article.

In any composite model, the constituents of dirons carry quantum numbers for metacolor, color, flavor, and generation, as well as spin. Which of these is fundamental, and which derived? In general, the model builders have made efforts to derive color and generation; the other degrees of freedom are usually taken to be fundamental. As I mentioned above, the attempt to interpret the order of the rishons as the color of the quarks failed. Models in which generation is not fundamental make use of the possibility of adding

extra neutral objects --- either single scalar particles with vacuum quantum numbers, scalar-antiscalar pairs, or fermion-antifermion pairs --- to the ground state configuration to get higher generations. In supersymmetric models, the fermion-antifermion pairs may be metacolor gluino-antigluino pairs. One might also suppose that generations are associated with orbital or radial excitations of the ground state; however, this naive picture leads to excitation energies of the order of the binding scale, which is orders of magnitude too large to be associated with the second and third generations of quarks and leptons.

Protecting diiron masses

Three mechanisms have been proposed to prevent dirons (quarks and leptons) from getting a mass of the order of the binding scale.

--- The first is chiral symmetry, as suggested by Gerard 't Hooft of the University of Utrecht, and by Savas Dimopoulos, Stuart Raby (now at Los Alamos) and Leonard Susskind of Stanford University. Many theories, including quantum chromodynamics and its analogues, have Lagrangians that exhibit chiral symmetry, that is, the Lagrangians are invariant under independent unitary transformations of their left-handed and right-handed spin-1/2 fermions. Mass terms do not have this invariance and break chiral symmetry. If the chiral symmetry is not dynamically broken, the theory yields massless spin-1/2 fermions; if these fermions can be provided with the proper quantum numbers, they can be identified with quarks and leptons. 't Hooft has pointed out a necessary, but not sufficient, condition for this to occur: The axial anomaly associated with the constituents must match the anomaly associated with the composites. Roughly speaking, 't Hooft's anomaly-matching condition is necessary for both the fundamental theory at the preon level and the effective theory at the diiron level to be consistent, renormalizable theories.

In theories --- such as quantum chromodynamics --- in which no bosons are present, and in which the left-handed and right-handed fermions have the same flavor quantum numbers, chiral symmetry is broken, as Donald Weingarten of IBM and Cumran Vafa and Edward Witten of Princeton University have shown. Furthermore, in theories in which all the preons are fermions, the anomaly-matching conditions are so restrictive that they only have bizarre solutions. Both these facts argue against models with only fermions. In boson-fermion models, however, the anomaly-matching conditions are easy to satisfy. In addition, the negative result of Weingarten and of Vafa and Witten has not been shown to hold for theories with scalars. Thus there is hope that chiral symmetry can protect quarks and leptons from getting large masses in such theories.

--- A second mechanism for getting low mass is the spontaneous breaking of supersymmetry which leads to massless Goldstone fermions called "goldstinos". This mechanism is unsatisfactory because it yields too few massless fermions: Only one goldstino can be generated for each broken fermionic supersymmetry generator.

--- The third mechanism, which has received a good deal of attention in the last two years, is the breaking of global symmetry in a supersymmetric theory. Breaking a global symmetry usually generates massless Nambu-Goldstone bosons, one for each broken generator. In a supersymmetric theory, these bosons are associated with fermionic partners, which are also massless. Several authors have constructed quasirealistic models using this mechanism and have shown that there is a neat way of associating the dirons of one generation with the set of fermionic Nambu-Goldstone partners generated in a simple symmetry-breaking scheme, namely the breaking of $SU(6)$ to $SU(4) \times SU(2) \times U(1)$.

Weak interactions

I suggested earlier two reasons not to consider the weak interactions as fundamental:

--- We have seen in the past that many short-range interactions are residual effects of compositeness at a deeper level of structure.

--- The W and Z particles that mediate the weak interactions can be constructed, in most models, from the same preons used to construct the dirons and the Higgs. Why not use this possibility?

I now want to consider this possibility more carefully, indicate what has to be required to make it work, and give a status report on the theory of composite W's and Z's.

I emphasize that considering weak interactions as residual while preserving electromagnetism as fundamental is a retreat from the partial unification of electroweak interactions which was considered one of the great successes of the 1970's. Nonetheless, the analogy between strong interactions as residual effects of color and weak interactions as residual effects of metacolor is so compelling that I would be willing to give up the partial unification.

To take this iconoclastic possibility seriously, we have to be assured that the results of the standard model, which uses a local gauge theory and accounts for all experiments done so far, can also be obtained without gauge theory, and that the alternative theory is not too ugly or complicated.

In 1978 James D. Bjorken of SLAC (now at Fermilab) showed that the standard model's description of weak interactions at low energy can be duplicated without a gauge theory provided one makes two assumptions:

--- There is a globally symmetric Fermi interaction involving an isospin-1 left-handed diron current.

--- There is a mixing of the neutral member of the current with the electro-

magnetic current.

The effective Lagrangian for weak interactions would then have the form

$$\mathcal{L}_{\text{eff}} = - \frac{G}{\sqrt{2}} \vec{J}_\mu \cdot \vec{J}^\mu .$$

Here \vec{J}_μ is the left-handed weak isovector diron current: For the first generation particles they have the form,

$$\vec{J}_\mu = (\bar{u} \ \bar{d}') \gamma_\mu \vec{\tau} \frac{(1+\gamma_5)}{2} \begin{pmatrix} u \\ d' \end{pmatrix} + (\bar{\nu}_e \ \bar{e}) \gamma_\mu \vec{\tau} \frac{(1+\gamma_5)}{2} \begin{pmatrix} \nu_e \\ e \end{pmatrix} .$$

Here the primes indicate that the quark fields are mixtures of strangeness conserving and strangeness-nonconserving components --- that is, rotated through the Cabibbo angle. Furthermore, the third component of the diron currents are replaced by a mixture of the weak and electromagnetic currents --- that is, the components are rotated through the weak mixing angle:

$$J_\mu^3 \rightarrow J_\mu^3 - \sin^2 \theta_W J_\mu^{\text{em}} .$$

For the first generation dirons, the electromagnetic current is

$$J_\mu^{\text{em}} = 2/3 \bar{u} \gamma_\mu u - 1/3 \bar{d} \gamma_\mu d - \bar{e} \gamma_\mu e .$$

Analogous expressions hold for the higher generations.

Bjorken suggested that the mixing could be due to the electric charge radius of the neutrino, and pointed out that a very large mixing is required. Pham Q. Hung (now at the University of Virginia) and Jun J. Sakurai of the University of California at Los Angeles carried Bjorken's suggestion further in the context of a model with explicit W and Z exchanges. They found, as did Bjorken, that asymptotic validity (at high energy) of the symmetry of the standard model, $SU(2)_L \times U(1)_Y$, considered as a global symmetry, gives the

same mass formula,

$$M_Z = \frac{M_W}{\cos \theta_W} ,$$

as the standard model. Further, again in agreement with Bjorken, they found that large photon- W^0 mixing can occur if there are large diiron-loop contributions to the photon vacuum polarization.

The work of Bjorken and Hung and Sakurai did not refer to composite W's and Z's. The idea that weak interactions are a residual effect of the compositeness of W's and Z's was first suggested by Harari and by Shupe in the context of the rishon model mentioned above; later Pati and, independently and in more detail, Joseph Sucher and I developed this idea at the University of Maryland in the context of the boson-fermion model that I am using as an example of preon models in this article. In this model, W's and Z's are constructed from the flavor carrying left-chiral spin-1/2 preons F_L , both because weak interactions have a chiral nature that can be carried by spin-1/2 preons and because using spin-0 preons would require a P-wave bound state whose wavefunction at the origin would vanish and force W^0 -photon mixing to vanish (or at least be small). In the model I have described, we construct the following left-handed triplet and singlet of spin-1 W's:

$$W_{\mu L}^{+,0,-} = (\bar{F}_{dL} \gamma_\mu F_{uL}, 1/\sqrt{2}(\bar{F}_{uL} \gamma_\mu F_{uL} - \bar{F}_{dL} \gamma_\mu F_{dL}), \bar{F}_{uL} \gamma_\mu F_{dL})$$

$$W_{\mu L}^1 = 1/\sqrt{2}(\bar{F}_{uL} \gamma_\mu F_{uL} + \bar{F}_{dL} \gamma_\mu F_{dL}) .$$

Analogous sets of spin-0 Higgs bosons can be constructed using $\bar{F}_L F_R$ and $\bar{F}_R F_L$, and similar sets of right-handed W's can be made from the right-chiral projections of the spin-1/2 preons F_R .

To make the weak interactions mediated by these composites mimic the standard model, we must require that

--- the left-handed triplet of W 's to be much less massive than the right-handed triplet

--- there be a large mixing between the W^0 of these triplets and the photon

--- the excited partners of all these particles (which must exist because we assume the preons are permanently confined) be much more massive than the ground-state W 's, so that only the ground-state W 's contribute to the weak interactions at low energy.

In some models, a linear combination of left- and right-handed singlets together with the neutral member of the right-handed isovector W is also required to be light. At first sight, this seems like a lot to ask; however, over the past four years, a number of authors, using several different arguments, have related these requirements to the conditions that the masses of the left-handed W 's be less by a factor of 5 to 10 than the compositeness scale, and that the other W 's and all the excited states lie at the compositeness scale or higher. I can't discuss this in more detail here. The interested reader can find the vector dominance point of view and references to earlier work in reference 7. The outstanding open questions are to show how the left-handed W 's can be made sufficiently light and why the observed W and Z masses agree so well (to about 5%) with the predictions from the standard model.

Searching for compositeness

If dirons are composite, evidence for compositeness will show up in the same experiments, which up to now have only provided constraints. Thus we will see deviations in $g-2$, we will find new contact interactions and we will observe rare decays. In addition, because the preons are confined, the compo-

site quarks, leptons, W's and Z's must have excited states in addition to the ground-state dirons, just as the ground-state baryons and mesons have excited states in quantum chromodynamics. The masses, spins, flavors and other quantum numbers of the excited states will be important clues to the correct preon model. Finally, just as the color-carrying particles, the partons (quarks and gluons), materialize through "hadronization" into pions, nucleons and other hadrons, the metacolor-carrying preons will materialize as dirons via "dironization." Figure 2 shows the analogy between these two processes. The experimental signature for dironization will be multiple production of quarks and leptons in multi-TeV e^+e^- colliders or at still higher energies in pp colliders, as illustrated in figure 2.

The history of elementary-particle physics lends support to the idea that properties which are not calculable in the standard model, such as the mass spectrum of quarks and leptons, can be understood by going to a deeper level of structure in which many of the particles of the standard model are composite. Present experimental data and theoretical understanding allow the hope that the next compositeness scale occurs at an energy close to a TeV.

I have described some of the models that have been constructed to account for the quantum numbers of quarks, leptons, W's, the Z, and scalar bosons in terms of constituents. Good progress has been made in finding symmetries that protect the masses of quarks and leptons from the large compositeness scale: in particular, chiral symmetry and the Nambu-Goldstone mechanism in supersymmetric models.

Although models with appealing features have been proposed, no model of quark-lepton physics so far has seemed as promising as the quark model was for hadron physics in 1964. The quark model required three surprising departures from previous models:

--- The fractional electric charges of the quarks
--- The existence of a hidden degree of freedom, color
--- The permanent confinement of colored quarks and gluons (a large-distance effect) together with asymptotic freedom at short distances, the vanishing of the "running" quark-gluon coupling constant.

We do not yet know what surprises are in store for us at the preon level. Further experimental and theoretical work will tell whether compositeness of particles in the standard model is relevant to the regime of physics now being entered by experiment.

Acknowledgements

I want to thank Chris Quigg for hospitality at Fermilab, and Yoichiro Nambu and Robert Sachs for hospitality at the Enrico Fermi Institute, University of Chicago. I am grateful to Rabi Mohapatra, Shmuel Nussinov, Jogesh Pati and Joseph Sucher for many discussions of preon models over several years. I thank Carl Albright, Estia Eichten, Chris Quigg and Jon Rosner for helpful comments on a draft of this article.

This work was supported in part by the National Science Foundation.

References

1. S. Weinberg, The Discovery of Subatomic Particles (Freeman, New York, 1983).
2. L. Lyons, in Progress in Particle and Nuclear Physics **10**, 227 (1983).
3. M.E. Peskin, in Proc. 10th International Symposium on Lepton-Photon Interactions at High Energy (1981), p. 880.
4. R.D. Peccei, in ECFA-CERN Workshop on Feasibility of Hadron Colliders in the LEP Tunnel, (CERN, Geneva, 1984), p. 329.
5. O.W. Greenberg, R.N. Mohapatra, and S. Nussinov, Phys. Lett. **148B**, 465 (1984).
6. See Supersymmetry and Supergravity, J. Wess and J. Bagger (Princeton, Princeton, 1983).
7. B. Schrempp and F. Schrempp, DESY preprint 84/055, May 1984.

Figure Captions

Fig. 1: Preon exchange graph which gives a contact interaction at low energy.

Fig. 2: Hadronization and Dironization.

Composites	Constituents	Binding forces
Matter	Molecules	van der Waals
Molecules	Atoms	Chemical
Atoms	Nuclei and electrons	Coulomb
Nuclei	Protons and neutrons	Nuclear
Hadrons	Quarks and antiquarks	Color
Quarks and leptons	???	Metacolor

Box 1: Five levels of structure of matter discovered so far.

	size r (cm) or inverse energy	mass M (MeV)	$mr = \frac{M}{\Lambda}$
H	0.5×10^{-8} or $(4 \text{ KeV})^{-1}$	940	2×10^5
p	10^{-13} or $(200 \text{ MeV})^{-1}$	940	5
e	$\lesssim 4 \times 10^{-17}$ or $(0.5 \text{ TeV})^{-1}$	0.5	$\lesssim 10^{-6}$

Box 2: Masses, sizes, and $mr = \frac{M}{\Lambda}$ for H atom, proton, and electron

u (5 MeV)	c (1.5 GeV)	t(30-50 GeV)
d (9 MeV)	s (180 MeV)	b (4.8 GeV)
ν_e (<30 eV)	ν_μ (<520 keV)	ν_τ (<164 MeV)
e (511 KeV)	μ (106 MeV)	τ (1.78 GeV)

Box 3: Lagrangian masses of fermions (quark masses are approximate)

Binding forces	Range	Reinterpretation of binding forces
van de Waals	short	residuals of Coulomb
chemical	short	residuals of Coulomb
Coulomb	long	remains fundamental
Nuclear (Yukawa)	short	residuals of color
Color	long	remains fundamental
Metacolor	long	remains fundamental

Box 4: Long- and short-range forces
